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A new concept for analyzing the energy efficiency of air-conditioning systems

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ABSTRACT

This paper sets the viewpoint of air-conditioning system from heat sources and humidity sources, especially focusing on the temperature distribution of heat sources and how it influences the efficiency of air-conditioning system. For humidity sources, they are different from heat sources for their physical essence, which provides the possibility of separate treatment of heat and humidity. This paper establishes the ideal air-conditioning system of cooling and dehumidifying, based on the ideal treatment of heat sources, and humidity sources. Then the difference between ideal system and actual system are explored by a case study showing the decrease of efficiency step by step. The gap between ideal system and actual system can be concluded into three main imperfections: the method of treatment of heat sources, transmission temperature difference and heat exchange temperature difference, and the energy consumption of transportation. In the last, according to the actual influencing factors, some improving directions are proposed to improve the current system correspondingly.

1. Introduction

In the conventional air conditioning system, the control strategy of indoor environment is close to form a uniform temperature and humidity environment by mixing the supply air with the indoor air completely. On the other hand, the heat sources of the indoor environment, including solar radiation, human beings, computer, light, envelope, etc., cover a large temperature range, which indicates the character of indoor environment is non-uniform and provides the possibility of using cooling sources in different temperature level. Moreover, cooling and dehumidifying are two major requirements of indoor environment control, but are different in essence. The difference of cooling and dehumidifying exists as the requirement of cooling grade. For example in condensing dehumidification the temperature of chilled water should be lower than the dew point of air to be treated, but for cooling the temperature of chilled water should be lower than air temperature.

Based on the character of non-uniform indoor heat sources and the essence of cooling and dehumidifying, considerable researches have been conducted in recent years. Relevant researches include the application of air terminal devices such as personalized ventilation [1] and displacement ventilation [2], which avoid the defects of traditional mixing air supply method. And radiant terminals such as radiant ceiling, radiant floor are also used to remove sensible cooling load, which aims at reducing fan and chiller energy consumption. The system of combined cooled ceiling and displacement ventilation [3] can provide better indoor air quality and thermal comfort with proper design, and the potential of reducing energy consumption depends on the supply air temperature, outdoor airflow rate, and cooling load. Dedicated outdoor air systems (DOAS) integrated with ceiling radiant cooling panels as a parallel sensible cooling system are being considered as an alternative to conventional variable air volume (VAV) systems for commercial buildings [4]. Hourly energy simulation predicts that the annual electrical energy consumption of the pilot DOAS/radiant panel cooling system is 42% less than that of the conventional VAV system with air-side economizer. Compared to a full air system a 30% reduction of energy consumption of radiant floor system was predicted during the design [5]. And radiant floor cooling system integrated with dehumidified ventilation can solve the problem of condensation on a floor surface by lowering the dew-point temperature [6]. The natural cooling strategies and efficiency are studied with application double-skin facade in office buildings [7], which studies the natural night ventilation possibility in related to the double skin orientation and the speed and orientation wind. Moreover, free-cooling is understood as a means to store outdoors coolness during the night, to supply indoors cooling during the day [8]. The use of PCMs is suitable because of the small temperature difference between day indoors and night outdoors. Free-cooling systems can generate significant savings [9], however, the amount of potential energy savings available depends almost totally on the overall system design and on the selection of equipment for use in the system.

This paper sets the viewpoint of air-conditioning system from heat sources and moisture sources, especially focusing on the temperature distribution of heat sources and how it influences the

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Nomenclature

$c_{p,a}$	heat capacity of dry air (kJ/(kgK))
$c_{p,v}$	heat capacity of water vapor (kJ/(kgK))
COP	coefficient of performance (dimensionless)
Ex	exergy (kJ/kg)
Q	heat (kJ)
r	latent heat of vaporization of water (kJ/kg)
R_a	gas constant for air (kJ/mol/K)
T	temperature (°C)
W	work (kJ)
ω	humidity ratio (kg/kg)

Subscript

c	cooling
d	dehumidifying
f	fresh air handling
i	ideal process
In	indoor air state
Out	outdoor air state
R	reference point

efficiency of air-conditioning system. Actually the energy-saving methods mentioned above are rooted in the non-uniform character of heat sources. The objective of this paper is to establish the ideal air-conditioning system of cooling and dehumidifying, based on the ideal treatment of heat sources, and humidity sources. The results of the work are most useful in hot and humid climate, where cooling and dehumidification are both important for air-conditioning system. Then the difference between ideal system and actual system will be explored and concluded in order to analyze the route from ideal to actual and the influences of actual factors. In the last, according to the actual influencing factors, some improving methods are proposed to improve the current system correspondingly.

2. Characteristics of indoor heat sources and moisture sources

The requirement of air-conditioning system is mainly consisted of two parts: removing indoor cooling load and moisture load, and handling outdoor air to meet the fresh air requirement of occupants. Indoor cooling load includes solar radiation, heat transferred from envelope, indoor equipments and devices, lights, occupants and etc. Indoor moisture load is mainly from occupants, and can from plants, open water, or infiltration air if there is any. For the handling of outdoor air, cooling and dehumidifying are required in humid climate. The indoor heat sources are different from each other in character, the studies of which include the research on solar radiation and its influence of cooling load [10], the researches of lights, equipments and human body [11–13]. One of the most important characters of indoor heat sources is the temperature, which is shown in Fig. 1 as the temperature distribution of various heat sources. As indicated by the figure, the temperatures of indoor heat sources cover a relatively large range, from around room

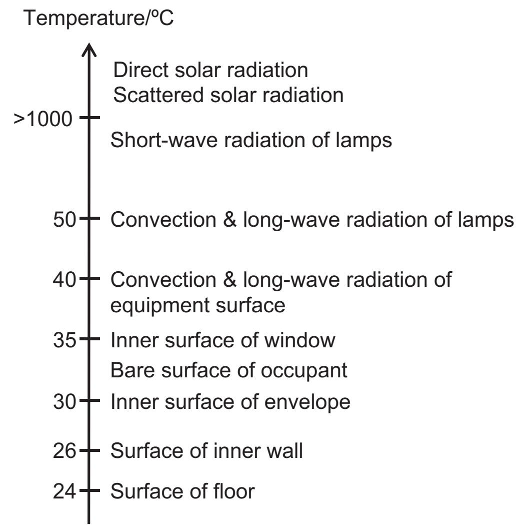

Fig. 1. The temperature distribution of various heat sources.

temperature to 50 °C. Short-wave radiation and solar radiation are quite deviated for its high temperature (over 1000 °C) from the temperature range of envelopes, equipments or occupants. Under this circumstances, considering the temperature character of heat sources and their relationship with indoor and outdoor condition, the heat sources can be divided into three groups: (1) short-wave radiation, which includes solar radiation and radiation of lamps; (2) high temperature heat sources, which mean the heat sources with temperature higher than outdoor air, including equipments, lights, occupants, etc.; and (3) low temperature heat sources, which mean the heat sources with temperature lower than outdoor air, including envelope, etc.

Three ratios can be defined to describe the feature of indoor sensible cooling load:

$$L_s\ \ (\%) = \frac{\text{Cooling load of solar radiation}}{\text{Total indoor sensible cooling load}} \times 100 \tag{1}$$

$$L_h\ \ (\%) = \frac{\sum \text{Cooling load of high temperature heat sourcesTotal indoor sensible cooling load}}{} \times 100 \tag{2}$$

$$L_l(\%) = \frac{\sum \text{Cooling load of low temperature heat sourcesTotal indoor sensible cooling load}}{} \times 100 \tag{3}$$

L_s indicates the percent of solar radiation in total cooling load for the very reason that solar radiation is different from all other heat sources in essence and many energy-saving devices such as radiant terminals, double-skin façade and etc. are directly connected with solar radiation. L_h indicates the percent of high temperature heat sources, which is a symbol of possibility and effectiveness of natural ventilation and free-cooling methods.

Considering moisture load of indoor environment, practically it is difficult to distinguish moisture sources in different humidity ratio as the way to classify heat sources by temperature. But it is necessary to mention that moisture load is different from sensible cooling load for its physical essence. In condensing dehumidification, the cooling and dehumidifying of air are achieved at the same time; however, this method ignores the difference of cooling and dehumidification. For cooling, the requirement of cooling source can be any source with lower temperature than air temperature. For dehumidification, the requirement of cooling source is the temperature lower than the dew point of air, which is directly related with the humidity ratio of air. Since the temperature of cooling sources is one of the most important influencing factors of energy consumption, the different essence of cooling and humidifying provides the possibility of separate treatment of heat and humidity.